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Accuracy and Stability of Fringe Measurements in SIM

Xiaopei Pan and Michael Shao

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109

Abstract. In order to identify habitable planets beyond our solar system it is necessary to determine their masses. SIM PlanetQuest is the only space mission which can discover and measure planets as small and cool as those in our solar system. This mission, however, requires unprecedented accuracy of angular measurements to the level of a microarcsecond, which are three orders of magnitude better than accuracy of the recent space astrometric missions. For microarcsecond accuracy of astrometric measurements the corresponding fringe delay must be determined to the accuracy of picometers, and it is a challenging task to measure fringe delays to this level of precision. Several testbeds in SIM have been established in order to check critical techniques and to validate estimation of fringe parameters. Many instrumental errors such as beam walk, cyclic errors, vibrations, alignment errors, visibility losses, wavefront distortions, and thermal drift are investigated. Also lessons learned from the Hipparcos mission lead us to further study of possible systematic biases. By using Full Aperture Metrology (FAM) wavelength calibration we show significant differences between stability and systematic offset of fringe measurements. A new calibration procedure is proposed.

1. Introduction

In the past decade more than 150 extra-solar planets (exoplanets) have been discovered(Jean S. 2005). It is important to know their physical characteristics, and how those exoplanets form and evolve. So far all exoplanets have been gas giants, and have temperatures of more than 1000 degrees. Are there any rocky and habitable exoplanets? To answer all questions above we must have SIM PlanetQuest(JPL Pub 1999), which is the only space mission dedicated to discover and to measure habitable exoplanets. In order to detect the astrometric signature of exoplanets the SIM instrument must reach microarcsecond astrometric accuracy.

For astrometric observations, measurement errors are devided into two catagories: systematic biases and random errors. In theory the systematic biases are fixed, and can be corrected. So most of studies have paid great attention to improve measurement stabilities, and to reduce the random errors, which include photon noise, read noise, perturbations, etc. In practice, however, the more challenging issue is how to improve measurement accuracy. A good example is the distance to the Pleiades cluster measured by Hipparcos mission. The Pleiades open cluster are concentrated in 4 pc in diameter. The Hipparcos project has determined distances for more than 50 Pleiades members with precision of a milli-arcsecond(mas), which is the best data at that

time. It is natural to average those 50 Pleiades stars' distances in order to get better distance of the Pleiades center. The results from Hipparcos are 118 ± 4 pc(Perryman et al. 1997). Unfortunately that result brought huge controversy in astronomical community. Fortunately, ground-based long baseline interferometers can provide angular measurements of sub-mas precision. The results from interferometers(Pan et al. 2004) indicate the distance to the center of the Pleiades is 132 ± 4 pc by measuring binary star Atlas, which is close to the center of the Pleiades. Why do the Hipparcos results have 10 % errors? Many studies have demonstrated that the problem come from accuracy analysis in Hipparcos! The claimed 1 mas error from Hipparcos is not a random error, and cannot be improved by averaging. Most of bright members of Pleiades stars, which have had better signal-noise ratio, suppose to provide more weights for determination of the Pleiades distance. The fact is that all of them have larger biases. The lessons learned from Hipparcos are important, i.e. good measurement stability can not guarantee absolute accuracy. SIM PlanitsQuest mission face the same problem on the issue of stability and accuracy.

2. WL fringe model and effective wavelengths

SIM instrument cover wide wavelengths from 400 nm to 1000 nm in order to gather more photons. For the current MAM testbed, the wavelength bandwidth is about 250 nm centered around 820 nm. The optical componets of SIM include many mirrors, beam splitters, prism, and detectors, and their responses are all wavelength dependent. In addition different stars have quite different spectra. It is not appropriate to assume a monochromatic light beam for the fringe detection if we want to reach pm precisions. For a pixel of CCD detector the mean bandwidth is about 7 nm for SIM and MAM. SIM use a pathlength modulation for multiple scans and mutiple dither steps. For the pixel j, photon counts F of white light(WL) fringes is a function of wave number w, stroke length d, band width B,dark current R, dispersion P and envelop function E, and can be described as follows:

$F(w, d, B, R, P, E) = a_0(1 + V_0 E(B, d)\sin(wd + \phi(w)))$, where intensity $a_0 = \frac{B}{2\pi}\int_{w_{j+}}^{w_{j-}} S(w)T(w)dw - R$, and w_{j-} and w_{j+} are minimum and maxmum wave numbers of that pixel, and R is background and dark current, and S(w) and T(w) are stellar emission and instrument throughput, respectively. The effective wavelength $\lambda_0 = 2\pi/w_0 = \frac{\int_{\lambda_j+B/2}^{\lambda_j-B/2} \lambda S(\lambda)T(\lambda)d\lambda}{\int_{\lambda_j+B/2}^{\lambda_j-B/2} S(\lambda)T(\lambda)d\lambda}$. The key parameter, fringe phase, $\phi(w) = \phi_0 + P(w)$, where optical delay $OPD = \lambda_0\phi_0/(2\pi)$, and delay dispersion P(w) depend on optical design and alignmnt. Normerized visibility can be computed as $V_n = \frac{\int_{w_{j+}}^{w_{j-}} V(w)S(w)T(w)dw}{\int_{w_{j+}}^{w_{j-}} V(w)S(w)T(w)dw}$, and the envelop function, $E(B, d) = \frac{B}{2\pi}\int_{w_{j+}}^{w_{j-}} V_n(w)e^{-j(w-w_0)d}dw$.

By using the formulas above the simulated fringe data are very much similar to the true measurements from MAM experiments. Based on that fringe model we can have good estimate of wavelength and optical delays.

3. FAM wavelength measurements

In order to investigate the issue of systematic biases and stabilities of fringe measurements in SIM. We carried out many experiments on FAM's wavelength in MAM testbed. In MAM, a coherent full-aperture metrology (FAM) beam is generated by frequency-doubling the 1319 nm Nd:YAG laser source. FAM's wavelength serves as standard to check systematic offsets in MAM WL measurements. Figure 1 presents the stability of FAM wavelength measuremnts in stroke lengths of $8\mu m$ and $16\mu m$,respectively. Both stabilities follow white noise model, and represent excellent determination of FAM wavelengths. For $8\mu m$ and $16\mu m$ strokes the FAM wavelengths are determined to the precisions of 122 pm and 41 pm at sampling time of 5 seconds, respectively. As we can anticipate that the stability in $16\mu m$ stroke are better than that in $8\mu m$. It is clear in Figure 1a that the FAM wavelength can be determined to a few pm for sampling time longer than 100 s. The values of wavelength bias, however, are quite different, as shown in Figure 2. FAM's wavelength has been measured by a high-resolution spectrometer in MAM lab as 1319.085/2=659.542 nm, and estimated wavelength offset is less than 0.1nm(Zhai 2002). Based on that independent determined FAM wavelength we can check about systematic offset for FAM's wavelength in MAM. The results in Figure 1b indicate that wavelength offset from $8\mu m$ stroke is 55pm, and offset from $16\mu m$ is 10 pm. We can notice that the offset at $10\mu m$ is larger than that at $8\mu m$. More interesting fact is that the wavelength offsets at $20\mu m$–$22\mu m$ are all larger than that at $16\mu m$. Are those just some obvious anomalies in data(Milman M. et al 2004)? Since wavelength bias at $16\mu m$ is the best, does that mean we should select $16\mu m$ stroke length as norminal case for future tests and data processing?

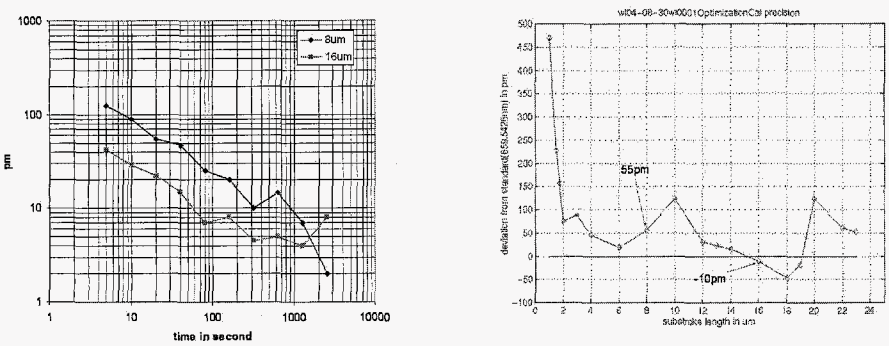

Figure 1. *a:* stability of wavelength measurements. *b:* wavelength biases vs. stroke lengths

By using models from polychromatic light we generate WL fringes for pixels 10 – 40. We use PSA techniques(Pan 2005) to determine wavelengths for all pixels. Figure 2a shows the wavelength biases for the pixel 30 – 32 which have better signal-noise ratio. As we can anticipated that the longer stroke length, the better accuracy of wavelength determination. The simulations demonstrate that at certain long stroke (for example $14\mu m$) the wavelength bias may worse than that from the short stroke($12\mu m$). But those are not anomalies in data. The range of fluctuations of wavelength biases represents the accuracy of wavelength

determinations. We can see in Figure 2a the accuracy after $16\mu m$ is bettern than 10 pm. As comparison, the results in Figure 1b demonstrate wavelength biases of around 100 pm. It is important to emphersize that the stability of FAM wavelength determination can reach 10 pm or less. But the wavelength biases is around 100 pm only. That conclusion also can be seen from WL wavelength determinations. Figure 2b presents comparisons of measured WL wavelengths against that from PSA techniques. For stroke length short than $6\mu m$ wavelengths have biases of more than 1000 pm. For the stroke of $16\mu m$ and $20\mu m$ the fluctuations and systematic offsets are much better than the short stroke, and estimated biases are around 200 pm(p-p), which has similar order of measurement accuracy to FAM's wavelength.

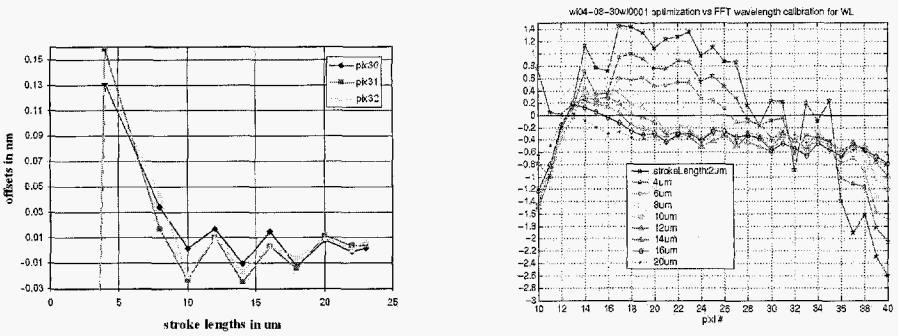

Figure 2. *a:* wavelength biases vs. stroke lengths. *b:* Comparison among WL wavelength biases

4. Conclusions

A new proposed fringe calibration procedure is based on the assumption of polychromatic light beams. The first step is to determine the effective wavelengths to the precision of 10^{-6}. The second step is to measure delay dispersions to accuracy of pm level. The third step is to calibrate biases caused by stellar spectra. The final OPD value is the weighted averages of multiple channels. From measurements of FAM wavelength determination it is recorgnized that the stability of pm level is reachable. The crucial point here is to correct systematic biases of fringe measurements.

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